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Bioreducer use in Finnish blast furnace ironmaking – Analysis of CO_2 emission reduction potential and mitigation cost

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HIGHLIGHTS

- Environmental and economic analysis of bioreducers is conducted.
- Carbon footprint of bioreducers is low compared to fossil-based reducing agents.
- EROI calculations suggest that production of bioreducers is energetically feasible.
- CO_2 reduction potential is highest with charcoal and lowest with torrefied wood.
- CO_2 mitigation cost of bioreducers is considerably high with current cost structure.

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ABSTRACT

Bioreducer use in the blast furnace could be one of the measures to decrease the fossil CO_2 emissions of steelmaking. This paper presents an environmental and economic evaluation of three bioreducers; charcoal, torrefied wood and wood-based synthetic natural gas (Bio-SNG), produced from logging residues, small-diameter wood and stumps. Additionally, the CO_2 emission reduction potential of these bioreducers is calculated, using Ruukki, a Finnish steel producer as a reference. Finally, we present the CO_2 mitigation cost for each bioreducer.

The Carbon Footprint (CFP) of the bioreducers without fertilizer production, carbon stock change and by-product credits is 7.2, 8.7, 8.5, 9.0 gCO_2/MJ for charcoal, 4.9, 5.2, 5.6, 5.4 gCO_2/MJ for torrefied wood and 7.4, 8.3, 8.2, 8.5 gCO_2/MJ for Bio-SNG, produced from logging residues, small-diameter wood with 30% and 50% moisture content and stumps, respectively. The CFP becomes larger when carbon stock change is taken into account; 45–117 gCO_2/MJ for charcoal, 27–61.0 gCO_2/MJ for torrefied wood and 32–79 gCO_2/MJ, for Bio-SNG. By-product credits can turn CFP to negative from −36.3 to −25.0 gCO_2/MJ for charcoal and from −2.7 to 4.7 gCO_2/MJ for Bio-SNG without carbon stock change and fertilizer use. Energy Return on Investment (EROI) of all the bioreducers is well above one, which means that production is energetically feasible.

Based on the Finnish example, the global CO_2 reduction potential could be up to 0.99–1.01 Mtons without and 1.29–1.39 Mtons with by-product credits annually. The CO_2 mitigation costs without by-product credits are 33–69 €/tCO_2, 22–53 €/tCO_2 and 112–150 €/tCO_2 and with by-product credits 26–54 €/tCO_2, 22–53 €/tCO_2 and 107–143 €/tCO_2 for charcoal, torrefied wood and Bio-SNG, respectively. Even though the CO_2 mitigation cost of bioreducers is considerably high in current cost structures, they provide a flexible alternative to CO_2 emission reduction in the steel industry.

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1. Introduction

Integrated steelmaking uses vast amounts of energy in the form of reducing agents. Integrated steelmaking refers to a production route where blast furnace (BF) technology is applied to produce hot metal, which is further refined into crude steel in a basic oxygen furnace (BOF). In many cases, integrated steel plants have also coking plants to produce metallurgical coke for BF process. Reducing agents used in the BF to reduce iron oxides are coke, coal, oil and natural gas. Metallurgical coke is the most expensive reducing agent and the production of coke causes various environmental impacts. Replacement of coke with injected reducing agents (coal,

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Nomenclature

C	plant investment cost with new capacity (€)
C_0	plant investment cost with initial capacity (€)
C_{IC}	capital investment cost including installation costs and working capital (€)
C_{Trans}	transportation cost (€/m^3)
C_{yearly}	annual investment cost (€)
F	annual demand for wood (m^3)
λ	fraction of the forest coverage dedicated for forest chips production (%)
i	interest rate (%)
n	scaling factor
N	lifetime of the plant (years)
S	new plant capacity (tDM/h)
S_0	initial plant capacity (tDM/h)
τ	tortuosity factor
x	transportation distance (km)
Y	annual yield of forest chips from the supply area (m^3/km^2)

Abbreviations

BAT	best available technology
BF	blast furnace
Bio-SNG	bio synthetic natural gas
BOF	basic oxygen furnace
CCS	carbon capture and storage
CFP	Carbon Footprint
CSC	carbon stock change
DM	dry matter
EROI	Energy Return on Investment
EU-ETS	European Union Emission Trading Scheme
HM	hot metal
ILUC	indirect land use change
LHV	lower heating value
LPG	liquefied petroleum gas
LR	logging residue
ORC	organic rankine cycle
PCM	phase change material
SDW	small diameter
ST	stump
TGR-BF	top gas recycling blast furnace
TCI	total capital investment
ULCOS	Ultra Low CO_2 Steelmaking

oil and natural gas) in the BF has been defined as a best available technique (BAT) [1].

Production of one ton of steel with BF-BOF route emits around 2.0–2.5 tons of fossil CO_2 emissions, depending on the technology efficiency, geographical location of the plant and emission allocation methodology [2–4]. The cumulative energy demand of steel production is 21.0–35.4 GJ/t steel [2,4]. Production technologies in integrated steelmaking have matured to the level where a further decrease in CO_2 emissions is rather difficult without drastic changes in technology [5]. As the blast furnace is the most energy consuming process in integrated steel plants [6], any attempts to reduce fossil CO_2 emissions should focus on this process.

In Europe, several ambitious objectives have been set to combat climate change. Examples include the 20–20–20 target and the 2050 Energy Roadmap [7,8]. The 20–20–20 target aims at 20% decrease in greenhouse gas emissions compared to 1990 levels, 20% share of renewables in energy production and 20% reduction of primary energy consumption by 2020 [7]. The 2050 Energy Roadmap describes the pathway towards a Europe that has decreased its greenhouse gas emissions by 80–95% by 2050 compared to the 1990 level [8]. The role of political incentives (e.g. European Union Emission Trading Scheme, EU ETS) may also play important role in the future towards CO_2-lean operational alternatives [9].

Several breakthrough technologies to decrease the CO_2 emissions in iron and steelmaking have been investigated in the context of Ultra Low CO_2 Steelmaking (ULCOS) program, including (1) blast furnace with top-gas recycling (TGR-BF), (2) a new smelting reduction process (HIsarna), (3) advanced direct reduction (ULCORED) and (4) electrolysis of iron ore (ULCOWIN and ULCOLYSIS). Additionally carbon capture and storage (CCS) has been evaluated as supporting technology to decrease CO_2 emissions [10]. Other measures to decrease CO_2 emissions and increase energy efficiency in iron and steelmaking include, e.g. the development of decision support systems [11] and development of waste heat recovery technologies such as use of phase change materials (PCM), methane reforming reaction and organic rankine cycle (ORC) to recover energy from molten slags and exhaust gases [12,13]. In addition to the above-mentioned technology development endeavors, interest in the utilization of renewable energy sources in iron and steelmaking processes to replace part of the fossil-based reducing agents and fuels has increased recently [14,15].

Charcoal use as a reducing agent in blast furnace ironmaking is not a newly adopted concept. Before the era of coal and oil, charcoal was used in small ironmaking processes (shaft furnaces), precursors of the modern blast furnaces [16]. Coke replaced the charcoal when blast furnace process developed to sizes where porous and mechanically strong support material was needed. Today charcoal is used in mini blast furnaces in Brazil [17], but not in modern, large-scale blast furnaces. It has been proposed in the scientific literature that charcoal could replace small portion of the top-charged coke or all injected reducing agents in the BF [14,18,19]. Charcoal could also replace a small share (~5%) of the coking coal in metallurgical coke production [20]. Further increase of the charcoal share weakens the mechanical strength of the metallurgical coke, which is prerequisite in the modern blast furnace [21]. Along with charcoal, also other biomass-based reducing agents (hereafter bioreducers), could be used in BF ironmaking. These bioreducers include bio-oil, torrefied biomass, syngas and bio synthetic natural gas (Bio-SNG) [14].

The main goal of using bioreducers is to decrease the fossil CO_2 emissions of steelmaking. One of the barriers in bioreducer use in iron and steelmaking industry is the economics of bioreducer use [14]. In this paper, we analyze the CO_2 emission profile, energy consumption and production costs of bioreducers, namely charcoal, torrefied wood and Bio-SNG, produced from Finnish wood-based feedstock. Additionally, we evaluate the CO_2 reduction potential achieved with each of the bioreducers by using Finnish steel producer as a reference. Finally we calculate CO_2 mitigation costs when replacing part of the metallurgical coke in the blast furnace with bioreducers.

2. Materials and methods

2.1. System description

The studied system includes all the energy and fuel inputs to produce charcoal, torrefied wood and Bio-SNG suitable for blast

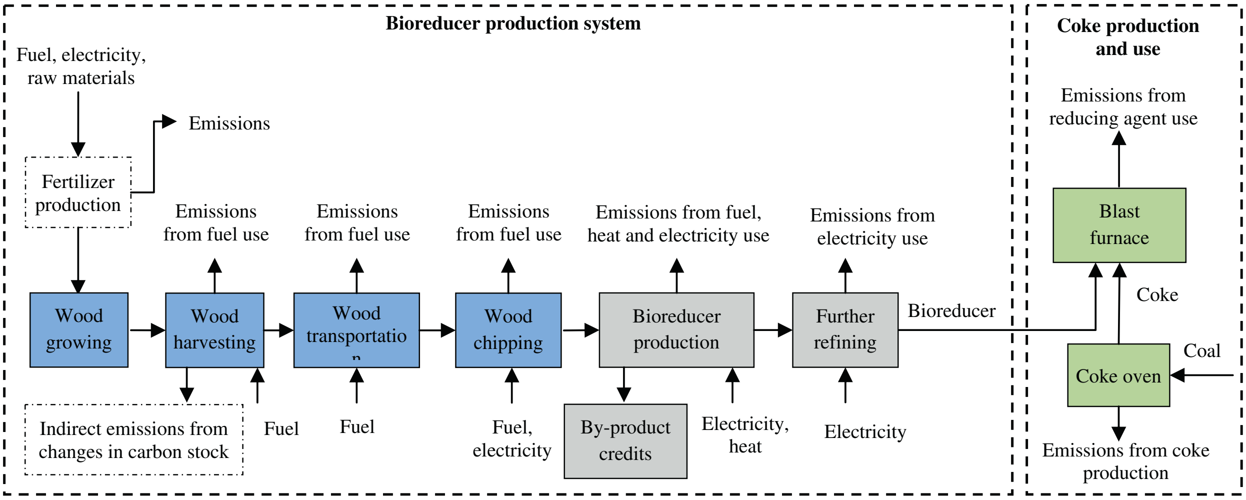

Fig. 1. System description of the study.

furnace reducing agent. In addition we include the coke production life cycle to our study to evaluate the CO_2 mitigation potential when replacing coke with bioreducers in the BF (Fig. 1). Emissions and energy consumptions are calculated per produced ton of bioreducer and one MJ of bioreducer (lower heating value). The base size of all the bioreducer production units is 50 MW (dry matter input).

Forest chip production system consists of several stages (blue boxes in Fig. 1), which are shortly described here. The first stage for small-diameter wood (SDW) and stumps (ST) is the harvesting and stump removal in the forest. Harvesting is done with a harvester that has a felling head designed for small-diameter wood. Stump removal and splitting is done with excavator that is equipped with extraction-splitting device. Logging residues (LR) do not need a separate harvesting stage as they are by-products of timber harvesting. Transporting to roadside is done with forest tractors. Operations at the roadside include drying of stumps from 50% to 30% moisture and loading of stumps into the stump truck. SDW and LR are chipped at the roadside. In case of small-diameter wood, we evaluate the direct chain and also the chain where wood is dried at the roadside from 50% (SDW 50%) to 30% (SDW 30%) moisture. Logging residues are assumed to be chipped and transported in 50% moisture. Long-distance transportation is done with dedicated stump and forest chip trucks. CO_2 emissions and energy use associated with forest chip production is viewed with different system boundaries. In the base case calculations, direct emissions from the forest chip supply chain and life cycle emissions from the fossil fuel use are taken into account. Additionally, the impact of nutrient compensation with fertilizers and indirect emissions from carbon stock changes (CSC) is evaluated (dotted boxes in Fig. 1). The CH_4 and N_2O emissions resulting from biomass storage are not taken into account, although dry material losses at the storage stage are accounted in the base scenario.

Three production technologies: slow pyrolysis, torrefaction and gasification + methanation are evaluated as technologies to produce bioreducers; charcoal, torrefied wood and Bio-SNG (gray boxes in Fig. 1). Slow pyrolysis of biomass is a technology where low heating rate is applied to produce solid char as a primary product at temperatures above 300 °C. In addition to the solid product, various tars and non-condensable gases are produced in slow pyrolysis, if gases are to be condensed [22]. Torrefaction is a thermal pre-treatment of biomass at low temperatures (<300 °C) and in the absence of oxygen [23]. In torrefaction, the moisture and part of the volatiles are removed from the raw material. Bio-SNG is produced from biomass via gasification and methanation [24]. It is possible to produce pure Bio-SNG (>95% CH_4), which could also be supplied to the natural gas grid. Further refining of torrefied wood and charcoal are also considered from the viewpoint of fuel consumption. Solid bioreducers must be pulverized before the injection into the blast furnace. Charcoal and Bio-SNG production yields by-products (pyrolysis gas, excess heat), which can be utilized in different applications. In this paper, it is assumed that by-products are utilized to produce electricity with 30% efficiency.

In order to evaluate the CO_2 reduction potential and mitigation costs of replacing coke in the blast furnace with bioreducers, a hypothetical scenario, based on the steel production volumes of Finnish steel producer Ruukki was used as a reference (green boxes in Fig. 1). Life cycle CO_2 emissions and production costs of metallurgical coke were established. Life cycle stages of the bioreducer production system were implemented in Factory Simulation Tool [25], which was also used in the calculation of bioreducer production plant mass and energy balances.

2.2. Evaluation methods

Three evaluation methods are used in our study. Carbon Footprint (CFP) is viewed here as a simplified life cycle assessment methodology with focus on carbon dioxide emissions. CFP is defined as CO_2-equivalent, which means that CH_4 and N_2O emissions are transformed into CO_2 equivalents by using defined coefficients [26].

Energy Return on Investment (EROI) is defined as an indicator to evaluate the energetic performance of different energy sources on a life cycle basis [27]. EROI defined here is the ratio of energy embodied in the products (bioreducer and energetic by-products) to the energy embodied in fuels (fossil-based) utilized to produce it (Eq. (1)).

$$\mathrm{EROI} = \frac{E_{bioreducer\ and\ by\text{-}products}}{E_{in,non\text{-}renewable}}, \tag{1}$$

where $E_{bioreducer\ and\ by\text{-}products}$ is the sum of the final energetic products and $E_{in,non\text{-}renewable}$ is the sum of the energy inputs needed to produce the fuel. The higher the EROI, the more efficiently the fuel is produced. The definition of EROI in this paper does not consider energy inputs of machinery and production plant construction, which are to be considered in full EROI calculation [28]. Life cycle stages included to the EROI calculation are presented in Fig. 1 and range from fertilizer production to further refining of the bioreducers. Energy inputs to the fuel and electricity production are also incorporated.

Economic evaluation of the bioreducers is based on production cost calculations with annualized investment, raw material and other operating costs. Investment cost C of the plant with a capacity of S is calculated according to Eq. (2).

$$C = C_0 * \left(\frac{S}{S_0}\right)^n, \tag{2}$$

where C_0 is the cost of plant investment with capacity S_0 and n is the scaling factor, which ranges from 0 to 1. The investment costs of the bioreducer production plants are transformed into present values (base year 2011) by using harmonized consumer price inflators (EURO 27 countries) [29]. Annual amortization of the investment is calculated with the following Eq. (3):

$$C_{yearly} = \frac{i(1+i)^N * C_{IC}}{(1+i)^N - 1}, \tag{3}$$

where C_{IC} is the capital investment cost including installation costs and working capital (15% of the fixed capital investment cost), i is the interest rate, N is the lifetime of the plant and C_{yearly} is the annual investment cost.

2.3. Forest chip production

For all wood-based raw materials, the following properties (ultimate analysis, dry basis) are assumed [30]: carbon (C) 52 wt%, hydrogen (H) 6.1 wt%, oxygen (O) 40.55 wt%, sulfur 0.05 wt% and ash (A) 1.0 wt%. The composition of the wood represents the average composition of softwood in Finland. The lower heating value of the wood is assumed to be 19.0 MJ/kg (dry basis). Forest chip production system productivities and energy consumptions are based mainly on Finnish data (Table 1).

Table 2
Dry-matter losses during the forest chip production stages.

Stage	Dry-matter losses (%)			
	LR	ST	SDW 50%	SDW 30%
Forwarding	2	1	2	2
Drying	–	3	–	10
Chipping	5	–	5	5
Loading	–	1	–	–
Long-distance transportation	2	1	2	2
Unloading	2	1	2	2
Crushing	–	2	–	–

During the different stages of forest chip production, there are dry-matter losses, which are taken into account in the calculations. Data is mainly collected from [40–42], but also own estimations are used in part of the stages (Table 2). Drying of the stumps and small-diameter wood (SDW 30%) at the roadside causes additional dry-matter losses.

Indirect emissions from carbon stock change are evaluated with the methodology described, e.g. in [43,44] and are taken as average of Northern and Southern Finland values with a 100 year time horizon. Indirect emissions occur, because energy wood (LR, SDW and ST) is burnt instead of letting it decompose in the forest. The carbon in the wood is released instantly to the atmosphere, instead of being released gradually through decomposition [43]. Calculated indirect emissions from carbon stock change are 74 kg/MW h,

Table 1
Productivity and energy consumption of forest chip production systems.

Phase	Action	Productivity	Energy consumption	Source
Forest operations	Thinning by harvester	9.5 (m^3/h)	12 (l/h)	[31,32]
	Stump removal	10.0 (m^3/h)	18 (l/h)	[33]
	Forwarding (logging residues)	10.6 (m^3/h)	10.0 (l/h)	[33]
	Forwarding (stumps)	7.0 (m^3/h)	10.0 (l/h)	[33]
	Forwarding (small-diameter wood)	11.8 (m^3/h)	9.5 (l/h)	[33]
				[34]
Operations at the roadside	Loading (stumps)	–	4.7 (l/load)	[35]
	Chipping (small-diameter wood)	80 (i-m^3/h)	40 (l/h)	[33]
	Chipping (logging residues)	80 (i-m^3/h)	40 (l/h)	[33]
Transport	Long-distance transportation Chips (small-diameter wood)	Load size 120 i-m^3	Fuel consumption is calculated according to load size, which is determined either maximum volume or mass. EURO 4 truck fuel consumption: empty 0.327 l/km and full (60 t) 0.496 l/km	[26,36,37]
	Long-distance transportation Chips (logging residues)	Load size 120 i-m^3		
	Long-distance transportation Stumps	Load size 150 i-m^3		
	Forwarder and harvester transportation	0.17 km/m^3	0.54 l/km	[38,39]
Operations at the use point	Unloading		1.7 (l/load) fuel	[35]
	Crushing (stumps)	200 (i-m^3/h)	1.05 (kW h/i-m^3) electricity	[36]

141 kg/MW h and 193 kg/MW h for LR, SDW and ST respectively [44]. CO_2 emissions resulting from fertilizer use are assumed to be 7 kg/MW h forest chips [45]. Primary energy consumption of fertilizer production is assumed to be same for every raw material; 1.4% of the delivered energy content in the forest chips [45].

2.3. Bioreducer production

Mass and energy balance modeling was conducted to all bioreducer production plants to produce data for carbon footprint, EROI and economic calculations. In the modeling of the bioreducer production plants it was assumed that raw material, i.e. wood is similar in respect of chemical composition and moisture. Depending on the raw material and on supply chain configuration, moisture content of the chips entering to the drying section is 30% or 50%.

The pyrolysis process was modeled based on the slow pyrolysis data provided by Demirbas [46] for beech and spruce wood. Apart from the mass balance, also the energy balance has been conducted for the pyrolysis process. The pyrolysis temperature is assumed to be 450 °C and the pyrolysis is assumed to be slightly exothermic (400 MJ/t dry biomass). Other assumptions are based on the work of Roberts et al. [47]. Mass yield of charcoal in 450 °C temperature is 30 wt% from dry biomass and LHV is 29.7 MJ/kg. Available by-product credits depend on the moisture of wood and, with 50% moisture wood, they are 5.5 MW h/t charcoal.

Modeling of the torrefaction plant was based on the data provided by Uslu et al. [48] and Bergman et al. [49] who have estimated mass and energy balances for 150 $MW_{thermal}$ torrefied wood production plant. Material and energy flows have been scaled according to capacity of 50 $MW_{thermal,\ dry\ biomass}$ plant. Torrefaction temperature is assumed to be 280 °C, resulting in mass yield of 70% from 15% moisture wood [48]. Lower heating value of the torrefied wood is 21.8 MJ/kg. Thermal efficiency of the torrefaction plant is 96% [49].

Mass and energy balances of the Bio-SNG production plant are mainly based on the work of Hacatoglu et al. [50]. Gasification technology is pressurized oxygen gasification and methanation is conducted in adiabatic reactors with intermediate cooling. Removal of water and carbon dioxide are also considered. Energy yield of the Bio-SNG was calculated as 70.5% from 15% moisture wood. The amount of excess heat is 0.97 MW h/t Bio-SNG when the moisture of the incoming wood is 50%. If the moisture of the wood entering to drying section is 30%, the excess heat amount is considerably higher, 3.1 MW h/t Bio-SNG.

The drying energy need is the same in all the cases (3.6 MJ/kg H_2O) and the raw material is dried from the initial moisture (either 30% or 50%) to 15% moisture before entering to thermochemical conversion. The heat for drying is taken from pyrolysis off-gases and from pyrolysis gas burning in charcoal production, from torrefaction gas and extra biomass burning in torrefied wood production and from exothermic heat available from methanation in Bio-SNG production. Other relevant data needed in the CFP, EROI and economic calculations are presented in Tables 3 and 4. Electricity produced from bioreducer production by-products are credited in marginal electricity production with emission factor of 600 $kgCO_2$/MW h [51]. High emission factor for marginal electricity results from the assumption that any addition to electricity production capacity would replace the most expensive electricity production capacity, which is load following power and produced from coal in condensing power plants [51]. Average emission factor for electricity is quite low in Finland because of the high share of nuclear, hydro and biomass-based electricity.

2.4. Coke replacement in the blast furnace with bioreducers

Typically used injected reducing agents (coal, oil, and natural gas) have different coke replacement ratios (amount of coke replaced by the injected reducing agent), depending on, e.g. chemical properties and heating value. Coke replacement ratio of oil, pulverized coal and natural gas is 1.17–1.2, 0.8–0.95 and 0.9–1.15 respectively [60,61]. Coke replacement ratio of charcoal is higher than that of pulverized coal, around 0.8–1.11 [62] depending on the carbonization degree and raw material properties. In this case, the replacement ratio of 0.95 is used, which is close to the replacement ratio (0.97) calculated earlier with blast furnace model [25]. Torrefied wood has low coke replacement ratio 0.4, due to high amount of oxygen and low calorific value [62]. Bio-SNG can be assumed to have the same coke replacement ratio as natural gas (1.05 is used). The selection of coke replacement ratios impacts on the final results when assessing the CO_2 reduction potential and mitigation costs of each bioreducer. In this analysis, representative values of coke replacement ratios presented in the literature have been selected.

Estimated amount of bioreducer use and their impact on coke consumption are summarized in Table 5, calculated with coke replacement ratios [61,62]. The base case reducing agent consumption is taken from [63]. It is assumed that oil injection is kept at constant level and coke amount is decreased when bioreducers are used. It was assumed that minimum coke rate in BF is 250 kg/tHM, which restricts the charcoal injection amount. Maximum charcoal amount is then 127 kg/tHM. Wiklund et al. [64] have shown that co-injection of oil and torrefied wood is viable

Table 3
Process data for bioreducer production plants.

	Value	Unit	Source
Electricity consumption (whole plant)			
Pyrolysis	150	kW h/t dry wood	Approximated from [52] for fast pyrolysis plant
Torrefaction	113	kW h/t dry wood	[53]
Gasification + methanation	330	kW h/t dry wood	[50]
Oxygen demand			
Gasification + methanation	710	m^3/t Bio-SNG	[54]
Wood consumption			
Pyrolysis	6.6	t/t charcoal	Calculated
Torrefaction	2.4	t/t torrefied wood	Calculated
Gasification + methanation	7.3	t/t charcoal	Calculated
External heat demand (forest chips)			
Pyrolysis	53	kW h/t charcoal	[47]
Torrefaction	933	kW h/t torrefied wood	Calculated
Electricity (grinding)			
Charcoal	21.5	kW h/t charcoal	[55]
Torrefied wood	150	kW h/t torrefied wood	[56]

Table 4
Emission factors and primary energy consumption of energy inputs.

	Value	Unit	Source
Emission factor for purchased electricity	210	$kgCO_2$/MW h	Average value of Finnish electricity mix [51]
Emission factor for marginal electricity	600	$kgCO_2$/MW h	Electricity produced from bioreducer by-products are credited with marginal electricity production [51]
Primary energy consumption of electricity production	8.46	MJ/kW h_e	[57]
Emission factor (LCA) of diesel production	0.69	$kgCO_2e$/l	Calculated from [58]
Primary energy demand of diesel production	1.29	MJ/MJ diesel	[59]

Table 5
Estimated bioreducer amounts in the blast furnace.

	Coke (kg/tHM)	Oil (kg/tHM)	Charcoal (kg/tHM)	Torrefied wood (kg/tHM)	Bio-SNG (kg/tHM)	Injected reducing agents (kg/tHM)	Total (kg/tHM)
Base case	370.0	85.0	–	–	–	85.0	455.0
Charcoal injection	250.0	85.0	126.8	–	–	221.8	461.3
Torrefied wood injection	334.0	85.0	–	120.0	–	205.0	527.0
Bio-SNG injection	265.0	85.0	–	–	100.0	185.0	450.0

with injection rates of 120 kg/tHM. Co-injection of oil and natural gas should also be technologically possible with proposed injection rates, based on the co-injection of coal and natural gas [65].

In our reference case, coke consumption with 2.3 Mtons annual hot metal production in two blast furnaces is 850,000 tons. Life cycle CO_2 emissions of coke production are assumed to be 673 kg/t coke [66]. The carbon content of coke is assumed to be 88%, which results in carbon dioxide emissions of 3.22 tons per used ton of coke in the blast furnace.

2.5. Production cost of reducing agents

By utilizing the estimated bioreducer rates in the BF and yearly hot metal production data, we can estimate CO_2 reduction potential from reducing agent production and use. Additionally, we use these figures to evaluate the CO_2 mitigation cost associated with replacing coke in the BF with bioreducers. We calculate the production cost of bioreducers by taking into account feedstock, plant investment and operating costs. We estimate the production cost of metallurgical coke by assuming that coking coal price is 180 \$/t (130 €/t) [67], which represents 51.4% share of production costs [68]. Investments needed in bioreducer injection equipment and preprocessing are ignored.

2.5.1. Forest chip cost

Forest chip costs are calculated from Finnish cost data [69] without road transportation costs (Table 6). The road transportation cost of forest chips is calculated with Eq. (4), presented by Petty and Kärhä [70].

$$C_{Trans} = 2.858 + 0.066x, \tag{4}$$

Table 6
Cost of the forest chips without road transportation [69].

	LR	SDW 50%	ST
Price (€/m^3)	16	31	23
Moisture (%)	50	50	30
Price (€/t) wet	19.6	37.9	39.4
Price (€/MW h)[a]	8.5	16.5	11.3

[a] Energy content (as received) of LR and SDW is 1.88 MW h/m^3 and 2.04 MW h/m^3 for ST.

where C_{Trans} is road transportation cost (€/m^3) and x is road transportation distance, in km. The assumed load size in the calculations is 42.5 m^3 for logging residues and small-diameter wood, which is roughly the average load size in Finnish forest chip transportation. It is assumed that road transportation costs are 15% higher for stumps. The average transportation distance in the base case is assumed to be 80 km.

Economy of scale of bioreducer production plants is assessed by taking into account the impact of unit size (Eq. (2)) and raw material costs. The supply area of forest chips is assumed to be a circle. The equation used in the calculation of average transportation distance to supply needed amount of wood is as follows:

$$x = \frac{2}{3}\tau\sqrt{\frac{F}{\pi\lambda Y}}, \tag{5}$$

where x is the average distance needed to supply enough wood to the charcoal plant, τ is the tortuosity factor that describes the actual distance traveled to the straight-line distance from the plant. F denotes the needed annual amount of wood (m^3). The forest coverage of forest chips that can be supplied is marked with λ and Y means the annual yield of forest chips from the supply area (m^3/km^2). A tortuosity factor of 1.0 describes a straight line between two points and 3.0 undeveloped road network [71]. Land area-weighting is incorporated in multiplier (2/3). In this work, a tortuosity factor of 2.0 is used. Values for λ and Y are calculated for whole Finland [72] and are 64.8% and 73.4 m^3/km^2 respectively. Forest chip cost is assumed to be 25 €/m^3 at roadside and transportation costs are calculated by using average road transportation distance x and Eq. (4).

2.5.2. Plant investment and operating costs

Investment costs of the pyrolysis plant are taken from the work of Roberts et al. [47], who analyzed a plant size of 10 ton dry matter per hour (tDM/h). They proposed that the investment cost for pre-treatment module is 3.6 \$M (2007 basis). The pyrolysis module (horizontal drum kiln) investment cost was 10.6 \$M (2007 basis). These values are used as base values for estimating the investment cost calculated with capacity factor (Eq. (2)). Monetary values are converted into Euros (2011 currency) and also the impact of inflation is taken into account. Investment costs of torrefaction plant have been taken from the work of Uslu et al. [48] and Bergman et al. [49]. According to the analysis of Bergman et al. [49], one production line is needed to capacities of 50–60 ktons of torrefied wood, which is in the range of the plant size in this paper. Torrefaction technology is a drum reactor for which Uslu et al. [48] have estimated investment costs of 7.5 €M (base year 2006). Investment costs of the Bio-SNG production plant are based on the work of Gassner and Maréchal [73]. According to their analysis, investment cost for a plant with a capacity of 20 $MW_{thermal,\ wood}$ would be 17.9 M€ (2006 base year). Their plant configuration included a steam circuit, which is assumed to be supplied by other party in this assessment. Investment cost used as a base value in this paper is the 17.0 $€M_{2006}$. Scaling factor *n* used in the plant sizing calculations is assumed to be 0.7, which is typical for biomass refining plants [48]. Other assumptions for process economic calculations are presented in Table 7.

3. Results and discussion

3.1. Carbon footprint of bioreducers

The carbon footprint of bioreducers differs significantly, which results from raw material demand, differences in product yields and energy demands. The CFP of bioreducers in base case without co-product credits, fertilizer use or indirect CSC is: 214.1–266.7 kg/t for charcoal, 105.9–122.3 kg/t for torrefied wood and 368.4–425.7 kg/t for Bio-SNG. The CFP calculated per produced unit of energy is 7.2–9.0 gCO_2/MJ, 4.9–5.6 gCO_2/MJ and 7.4–8.5 gCO_2/MJ for charcoal, torrefied wood and Bio-SNG in base case, respectively. The contribution of each stage of bioreducer production to CO_2 emissions in base case is depicted in Fig. 2. Supply chain CO_2 emissions contribute to about 25–49% of total CO_2 emissions in bioreducer production. Electricity use and resulting indirect CO_2 emissions are dominant in the Bio-SNG production. The share of CO_2 emissions from electricity use in Bio-SNG is 62%.

Only a small share of nutrient losses through the use of wood in Finnish forests is compensated by fertilization and it is not a recommended practice for energy wood use [76]. However, if fertilization use is incorporated in the CFP, the emissions are 321.1–383.1 kg/t for charcoal, 146.5–163.6 kg/t for torrefied wood and 486.3–553.6 kg/t for Bio-SNG. Indirect emissions from CSC increase emissions drastically. According to the assumption that the use of forest chips is continued for the next 100 years, the emissions are 1.3–3.5 tCO_2/t for charcoal, 0.6–1.3 tCO_2/t for torrefied wood and 1.6–4.0 tCO_2/t for Bio-SNG. Indirect emissions from soil carbon stock change are not currently taken into account in the EU legislation [76]. However, in the future, more emphasis may be laid to indirect land use change (ILUC). If the by-product credits are taken into account with the assumption that electricity is produced from by-products (fertilizer use and CSC ignored), a net credit will be gained with charcoal and Bio-SNG. The net impact of charcoal production would be from −1079.1 to −743.5 $kgCO_2/t$ and the net impact of Bio-SNG production from −125.6 to 234.5 $kgCO_2/t$.

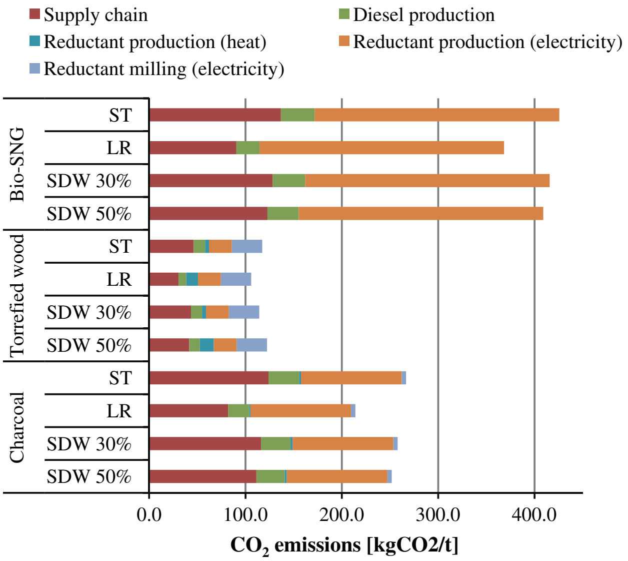

Fig. 2. Carbon footprint of charcoal, torrefied wood and Bio-SNG.

Table 7
Assumptions for process economics in base case.

Parameter	Value
Interest rate	10%
Discount period	20 years
Plant availability	90%
Operators + plant manager	12[a] + 1
Operator salary	60,000 €/year
Plant manager salary	70,000 €/year
Maintenance cost	4%/year of C_{yearly}
Electricity price[b]	85 €/MW h
Oxygen price[c]	0.058 €/m^3

[a] For a plant size of 50 $MW_{th,wood,\ dry\ basis}$. Scaling factor 0.7 is used for other production scales.

[b] The cost of electricity presents the electricity price for medium-scale industry in Finland [74].

[c] The same oxygen price is assumed for all capacities in Bio-SNG production [75].

An overview of the CO_2 emissions per produced unit of energy (gCO_2/MJ), with different stages taken into account, is presented in Fig. 3. The base case including fertilizer production, but no indirect emissions results in CFP of 10.8–12.9, 6.7–7.5 and 9.7–11.1 gCO_2/MJ for charcoal, torrefied wood and Bio-SNG respectively. If the indirect CSC is taken into account, but no by-product credits, the CO_2 emissions increase to 45–117 gCO_2/MJ, 27–61.0 gCO_2/MJ and 32–79 gCO_2/MJ for charcoal, torrefied wood and Bio-SNG respectively. The large variation in CO_2 emissions is due to the fact that LR, SDW and ST have different emission factors for CSC within a 100 year time horizon. For instance, the decomposition rate of logging residues is higher than that of stumps, which results in lower indirect emissions. As mentioned, by taking the by-product credits into account, CO_2 emissions of bioreducer production become negative in all charcoal production scenarios and in two Bio-SNG scenarios. From Fig. 3, where also the life cycle CO_2 emissions of natural gas (75 gCO_2/MJ) and coal (115 gCO_2/MJ) [58] are depicted, we can see that if indirect emissions from carbon stock change are strongly accounted, CO_2 emissions of bioreducer production become considerable. Compared to natural gas, charcoal produced from small-diameter wood and stumps has higher life cycle CO_2 emissions per produced unit of energy (gCO_2/MJ), charcoal produced from stumps even exceeds the life cycle CO_2 emissions of coal. As mentioned, it is unlikely that bioenergy carriers produced from energy wood will face such severe accounting of indirect emissions in the near future.

Carbon footprint of charcoal and Bio-SNG without by-product credits compare well to the values presented in the literature [3,50,77,78] despite the different raw materials and assumptions.

3.2. Energy return on investment

The EROI of bioreducer production is well above one for all raw materials and products (Fig. 4). The EROI values include also the energy embodied in fertilizer production. From the perspective of energy consumption, the production of bioreducers from wood-based biomass is feasible. The EROI of charcoal without

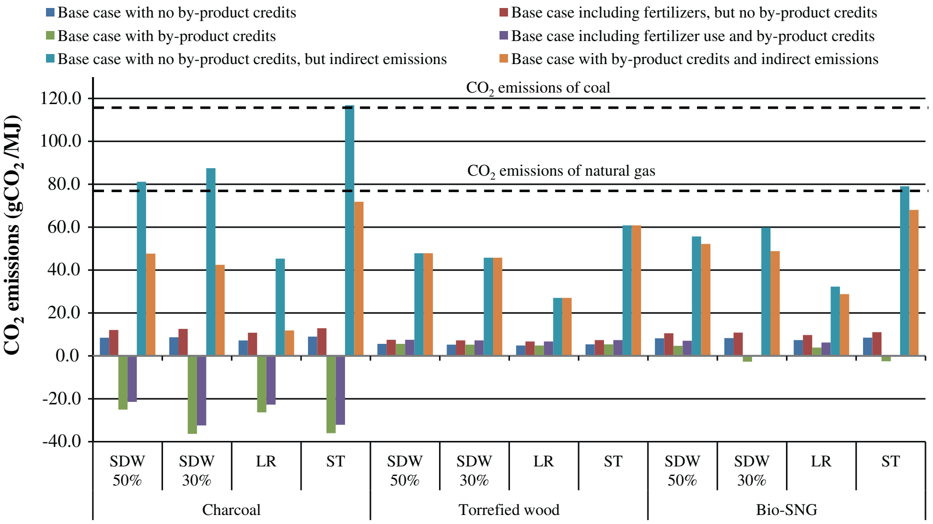

Fig. 3. CO_2 emissions of bioreducer production depending on system boundaries.

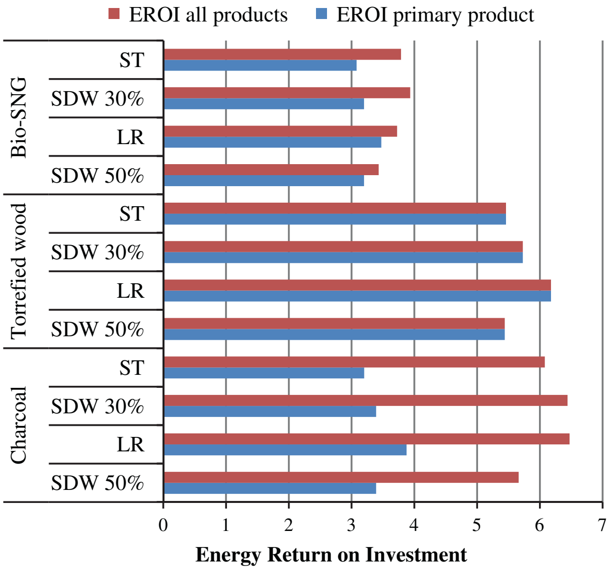

Fig. 4. EROI of bioreducers.

by-products (pyrolysis gas) is 3.2–3.9, depending on the feedstock. The EROI of Bio-SNG is slightly lower, 3.1–3.5, whereas the EROI of torrefied wood is the highest 5.4–6.2. This is because the energy yield of torrefaction is high and energy needed in the production stage is low. If the pyrolysis gas from charcoal production is taken into account, the total EROI of charcoal would be 5.7–6.5.

The EROI of charcoal and Bio-SNG have been assessed in some publications. High EROI, 15–35, was reported for charcoal produced in Brazil [79]. The net energy ratio of biochar was 2.8–3.1 in the work of Roberts et al. [47] and 5.3–6.9 in the work of Gaunt and Lehmann [80]. Fairly high EROI, 5.1–8.0, was reported for Bio-SNG [50].

3.3. Economics of bioreducer production

The total capital investment (TCI) cost for the charcoal production plant was calculated to be 12.6 $M€_{2011}$, based on the mass and energy balance calculation and plant costs derived from Roberts et al. [47]. TCI is at the same level as in the work of McCarl et al. [81]. Charcoal production costs range from 360 to 490 €/t charcoal, depending on the feedstock. TCI for the torrefaction plant was calculated to be 9.7 $M€_{2011}$. Investment costs, which are relatively low, were based on the work by Uslu et al. [48]. According to assumptions used in this research, the production cost of torrefied wood is 140–180 €/t. Higher investment costs have been proposed for torrefaction plants, e.g. in [82,83], which would result in higher production costs. TCI of Bio-SNG production plant are much higher than those based on pyrolysis or torrefaction, calculated as 38.0 M€ based on the data by Gassner and Maréchal [73]. Production cost of Bio-SNG is 690–830 €/t. Annual capital and operating costs for charcoal, torrefied wood and Bio-SNG with three raw materials (LR 50%, SDW 50%, ST 30%) are presented in Fig. 5.

Raw material costs are dominating in charcoal and torrefied wood production. This is also true in Bio-SNG production, but also capital costs contribute strongly to production cost. Production of charcoal yields excess pyrolysis gas that could be sold e.g. to energy production. The annual amount of pyrolysis gas in 9.5 tDM/h capacity charcoal plant available for selling is approximately 15.8 MW (when biomass moisture is 50%). In the work by Brown et al. [84], the price received from syngas was $5 MMBTU (comparable to the price of natural gas in US), which is approximately 13 €/MW h. In this analysis, the price of 20 €/MW h is assumed for the pyrolysis gas. Selling pyrolysis gas at 20 €/MW h can contribute to up to 35% of annual operating costs. The production costs of charcoal with pyrolysis gas credits subtracted are 250, 280 and 380 €/t for LR, ST and SDW, respectively. The difficulty related to pyrolysis gas as a fuel in a power plant is the storage. This deficiency can reduce its applicability as fuel compared to natural gas. If pyrolysis gas value is approximated to have a value below that of coal, i.e. 15 €/MW h, by-product credits can contribute up to 26% of operating expenditures.

Production cost of bioreducers is sensitive to plant size (Fig. 6). Depending on the cost structure of the thermochemical conversion plants, optimal bioreducer production cost is attained with varying plant capacities. Assumptions made in the economy of scale evaluation reveal that increasing the capacity of charcoal plant above 100 MW (21.5 tDM/h) biomass input does not bring any considerable additional value to charcoal production costs, however the lowest production cost are with around 160 MW plant capacity. In the case of torrefaction plant, the optimal size is around 100 MW (21.5 tDM/h) biomass input, but no noticeable decrease in production costs is achieved when capacity is over 70 MW. The production costs, however, do not increase significantly with

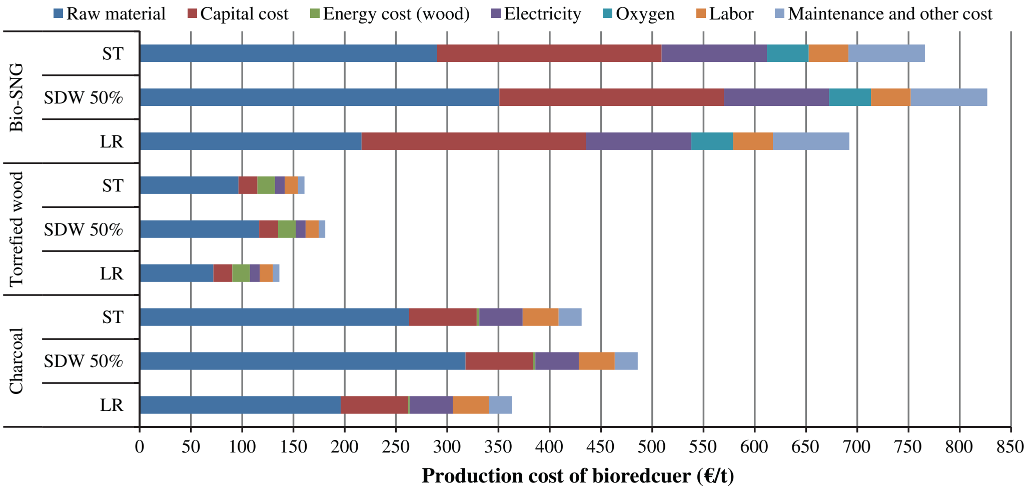

Fig. 5. Production cost of bioreducers (€/t) with base case plant size.

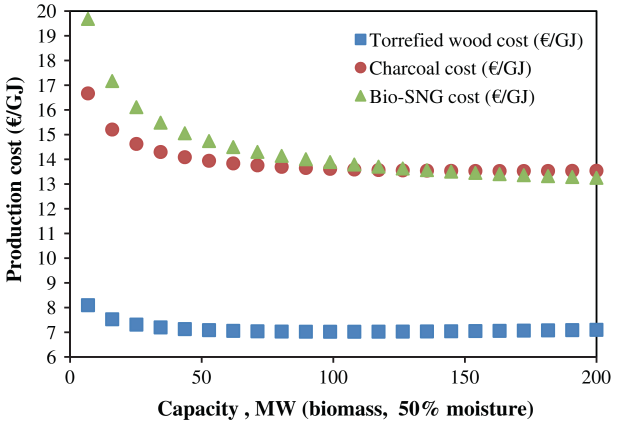

Fig. 6. Bioreducer production costs in relation to plant size.

larger capacities. Due to higher investment costs of Bio-SNG plant, larger plant sizes are favored. The lowest unit cost is achieved with 515 MW (104.0 tDM/h) biomass input.

In Finland, where the yield of forest chips from logging residues, small-diameter wood and stumps is quite low, the best option for charcoal and torrefied wood production could be decentralized plants with moderate capacities. In case of Bio-SNG production, larger plant sizes could be realized.

3.4. CO_2 reduction potential and mitigation cost

Life cycle CO_2 emissions from coke production stage are 573 ktons annually in our reference case. Eventually, almost all the carbon in the coke is released to the atmosphere during the iron and steel production processes. The amount of CO_2 emissions released from the coke use is above 2.7 Mtons annually. CO_2 emissions from coke production and use stages total around 3.3 Mtons annually. By replacing part of the coke in BF with bioreducers, fossil CO_2 emissions can be reduced significantly. Coke consumption would be reduced by 276, 110 and 242 ktons with charcoal, torrefied wood and Bio-SNG injection respectively. The coke replacement ratios in these calculations were 0.95, 0.4 and 1.05. In the assumptions we defined the minimum coke rate to be 250 kg/tHM with constant oil injection (85.0 kg/tHM), therefore, the maximum reduction in coke consumption is independent of the selected coke replacement ratio for charcoal. Only one coke replacement ratio for torrefied wood was found from the literature. The range of coke replacement ratios for Bio-SNG was 0.9–1.15. The reduction of coke consumption is then 207–265 ktons. For the sake of simplicity, we assume that deficit of coke oven gas (by-product of coke making), used as a fuel in steel production processes, is replaced by renewable energy sources with the cost of the coke oven gas. By using charcoal to replace part of the coke in Finnish blast furnaces, the amount of global fossil CO_2 emissions from reducing agent production and use could be reduced by 0.99–1.01 Mtons without by-product credits and by 1.29–1.39 Mtons with by-product credits. CO_2 mitigation potential with torrefied wood is lower, 0.40 Mtons per year. This is because coke replacement ratio of torrefied wood is lower than with charcoal. The amount of fossil CO_2 that could be reduced with the use of Bio-SNG is 0.84–0.86 Mtons annually without by-product credits and 0.89–0.97 Mtons with by-product credits.

The CO_2 emission mitigation costs with different bioreducers were calculated by comparing the increase in reducing agent production costs with CO_2 emission mitigation potential. CO_2 mitigation costs without by-product credits are 33–69 €/tCO_2, 22–53 €/tCO_2 and 112–150 €/tCO_2 for charcoal, torrefied wood and Bio-SNG respectively. With by-product credits the CO_2

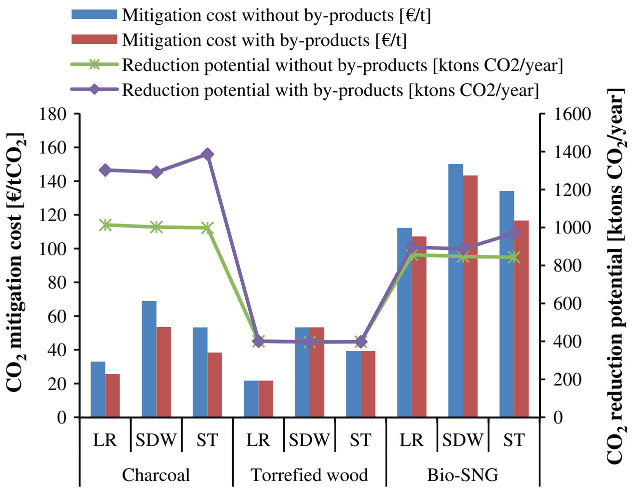

Fig. 7. Global CO_2 reduction potential and mitigation cost.

mitigation costs are 26–54 €/tCO_2, 22–53 €/tCO_2 and 107–143 €/tCO_2 for charcoal, torrefied wood and Bio-SNG respectively. Global CO_2 reduction potential and mitigation cost of bioreducers are compared in Fig. 7.

The coke replacement calculations in this paper represented the anticipated maximum amounts of bioreducer introduction into the BF when also oil is used as injected reducing agent. In summation, the economic performance of Bio-SNG as reducing agent is the worst. The production cost of Bio-SNG becomes high due to heavy investment costs and use of electricity and oxygen. Bio-SNG use could be economically more competitive when replacing liquefied petroleum gas (LPG) in reheating furnaces [15]. The CO_2 mitigation cost is lowest for torrefied wood. However, the CO_2 reduction potential with torrefied wood does not reach the potential of charcoal and Bio-SNG. Charcoal has the highest potential to decrease CO_2 emissions. Direct emissions could be reduced by 890 ktons in our reference case, which is 1.45% share of the Finnish total CO_2 emissions in 2012 [85]. In plant scale, direct CO_2 emissions could be reduced by 23.4% from 2012 level [86] with charcoal use, which can be considered as a substantial reduction.

Despite the fact that bioreducers do not seem to be economically feasible today, they outperform some of the other measures to mitigate CO_2 emissions in the steel industry. For example CCS involves heavy investments in infrastructure and large scale solutions are still scarce. In addition, possible areas for CO_2 storage are limited, which results in excessive transportation. Tsupari et al. [87] have calculated that the cost of globally avoided emissions with CCS in steel plant could be even above 100 €/tCO_2, depending on the captured CO_2 amount, technology, electricity price and so on. Compared to the calculated CO_2 mitigation costs with bioreducers, it seems that at least charcoal and torrefied wood use as reducing agents would be more feasible measure than CCS. Bioreducer use can be facilitated with gradual increase in injection amounts, since co-injection of fossil-based and biomass-based reducing agents is viable option [14,65].

4. Conclusions

Steel production with integrated BF-BOF route emits considerable amounts of fossil CO_2 emissions to the atmosphere. One solution could be the partial replacement of fossil-based reducing agents with bioreducers. In this paper, the environmental and economic performance of bioreducers, namely charcoal, torrefied wood and Bio-SNG, produced from Finnish wood-based raw materials (logging residues, small-diameter wood and stumps) was conducted. Life cycle based Carbon footprint and Energy Return on Investment calculations were conducted to evaluate the environmental impact of bioreducer production. Production costs for each bioreducer were calculated based on the developed mass and energy balance models.

The CFP calculations showed that there is a substantial potential to decrease the fossil CO_2 emissions of steelmaking by utilizing bioreducers in the BF. In addition, the EROI calculation confirmed that production of bioreducers from wood-based feedstock is feasible from an energetic point of view. Torrefied wood has the lowest CO_2 mitigation cost, but its ability to replace coke in the BF is minor, resulting low emission reduction potential. Bio-SNG works well as a BF reducing agent, but its mitigation cost is considerably higher than with torrefied wood and charcoal. Charcoal can be used in larger amounts than torrefied wood and Bio-SNG, which results in higher direct and also global CO_2 emission reduction potential. The CO_2 mitigation cost of charcoal is slightly higher than with torrefied wood but considerably lower than with Bio-SNG. It is concluded that bioreducers provide an efficient measure to reducing fossil CO_2 emissions in iron and steelmaking industry. While the economic competitiveness of bioreducers is currently unfavorable when compared to fossil-based reducing agents; this might change in the future, in light of the low carbon economy pursuit of Europe.

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